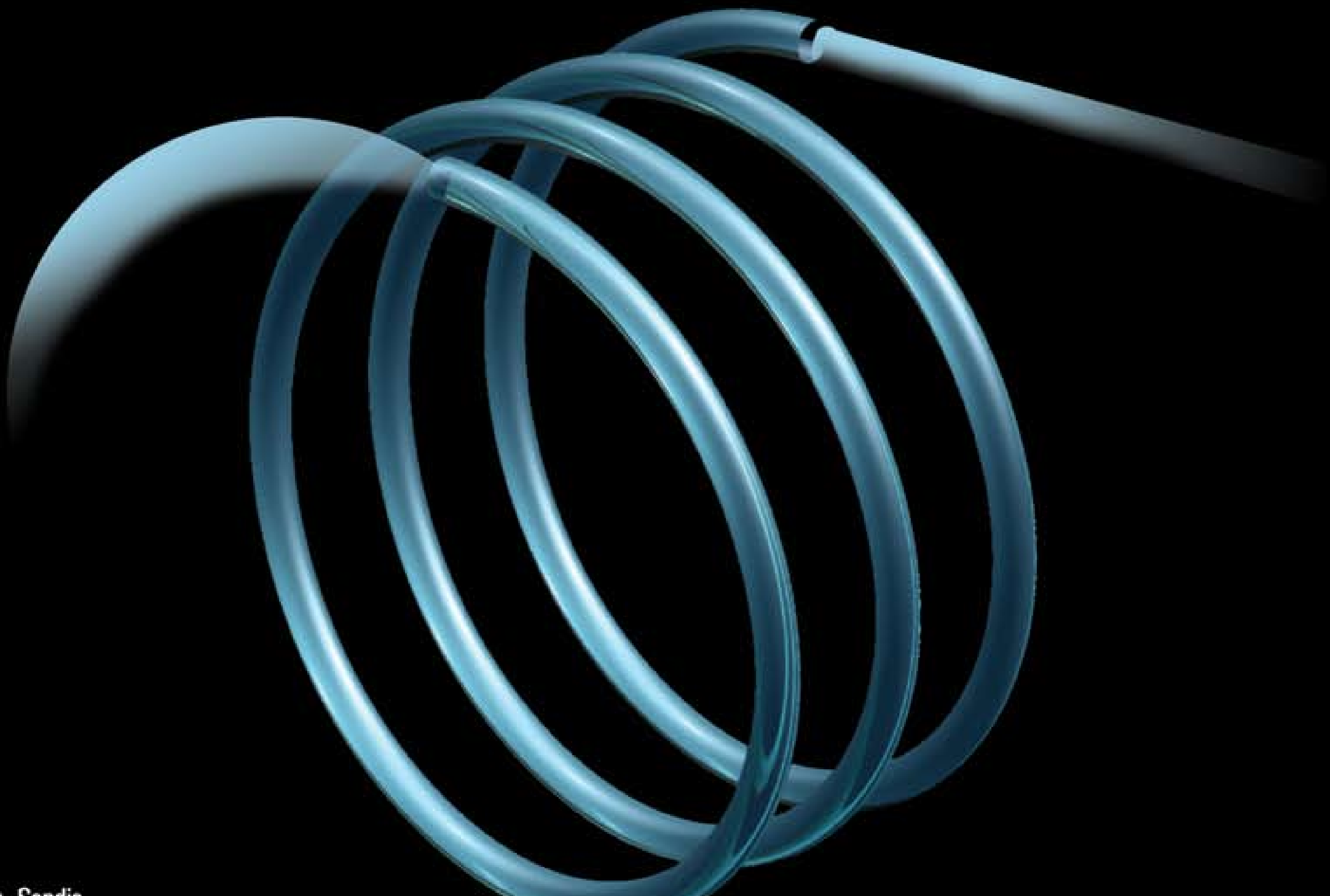
R&D 100 AWARD ENTRY 2007

MODE-FILTERED FIBER AMPLIFIER



Sandia National Laboratories

MODE-FILTERED FIBER AMPLIFIER

Submitting Organization

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AFFIRMATION: I affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

(Signature)______________________________

Joint Entry

Naval Research Laboratory (NRL), Nufern Corporation, and Liekki Corporation

Sandia and NRL are co-inventors of the Mode-Filtered Fiber Amplifier technology described in this application; the patent for this technology is held by the U.S. Government and is currently administered by NRL. Liekki and Nufern are licensees who produce commercial products using the subject technology.

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Mode-Filtered Fiber Amplifier

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Product Name

Mode-Filtered Fiber Amplifier

Brief Product Description

The Mode-Filtered Fiber Amplifier is a breakthrough technology that enables fabrication of practical, high-power, high-beam-quality laser sources that are compact, rugged, and extremely efficient.

Product First Marketed or Available for Order

The first commercial license for this technology was granted in 2005, and the first commercial products were offered by co-applicants Nufern and Liekki in 2006.

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Product Price

Sandia National Laboratories and NRL do not sell commercial fiber amplifiers; rather their government-owned technology is licensed to commercial partners. Liekki and Nufern have licensed the patent and manufacture a number of products that employ the mode-filtering technology. These products range from mode-filtered fiber coils (for incorporation into lasers and amplifiers by other companies) to complete laser systems. Liekki and Nufern also produce fibers whose design is optimized for mode filtering; these fibers are sold to manufacturers of lasers and laser-based instruments, as well as to R&D organizations.

Patents or Patents Pending

The patent related to this technology is U.S. 6,496,301: Helical Fiber Amplifier, invented by Jeffrey P. Koplow, Dahv Kliner, and Lew Goldberg, issued December 17, 2002 (see Appendix A for an image of the first page).

Mode-Filtered Fiber Amplifier

Product's Primary Function

Since their invention in 1963, fiber lasers have been recognized as possessing extraordinary attributes that could revolutionize the application of lasers to real-world problems by enabling compact, rugged optical sources with high beam quality. Fundamental limitations of previous fiber-based laser technologies, however, rendered impractical numerous high-power laser applications. The Sandia/NRL Mode-Filtered Fiber Amplifier enables dramatic power scaling of fiber lasers (by more than 100x), thereby addressing these long-standing limitations and making real-world applications practical. In particular, Mode-Filtered Fiber Amplifiers offer:

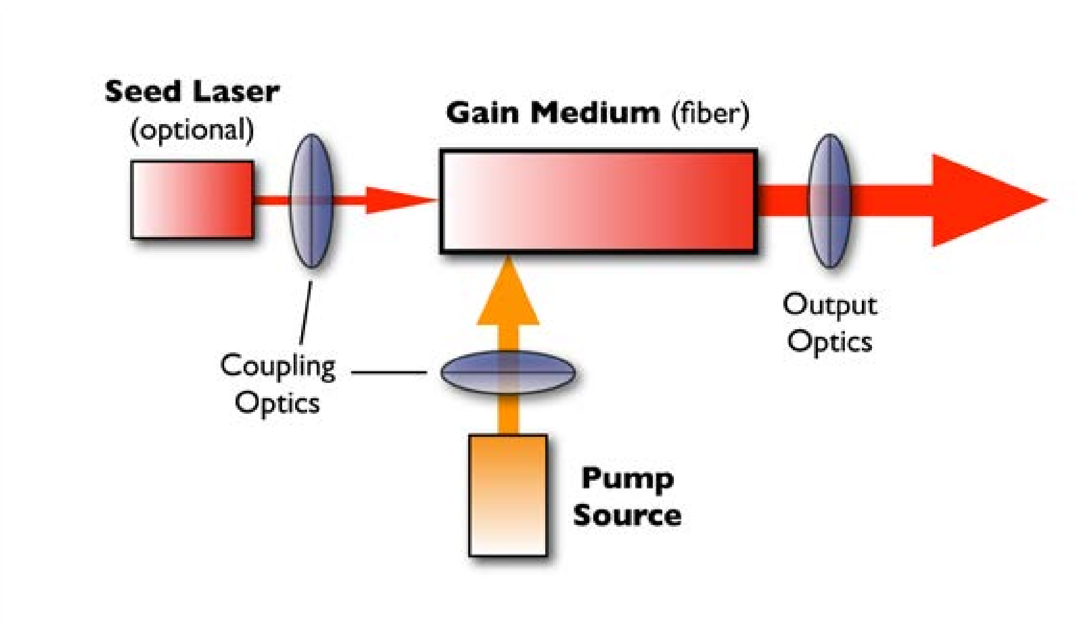
- High electrical efficiency (5x improvement over conventional solid-state lasers);
- Low waste-heat generation and facile thermal management;
- High optical gain;
- Broad wavelength coverage; and
- Diffraction-limited beam quality (explained below) that is insensitive to environmental or operating conditions, such as vibrations, thermal fluctuations, and optical power level.

— all in a package that is an order-of-magnitude smaller than traditional solid-state laser sources. As a result of this unique combination of characteristics, the Sandia/NRL invention has been licensed and commercialized by five companies, including co-applicants Liekki Corporation and Nufern Corporation.

Mode-Filtered Fiber Amplifier

Product's Primary Function

Figure 1a: Key components of a high-power laser system.



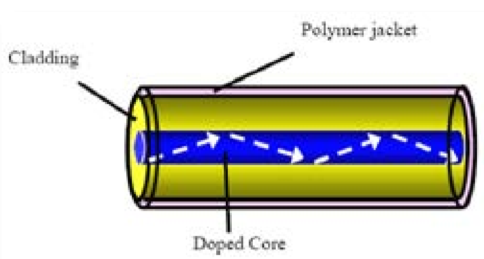


Figure 1b: Fiber gain medium

How Fiber Lasers Work

Figure 1a illustrates the basic components of a high-power laser system. In the case of a fiber laser, the gain medium is an optical fiber, consisting of a glass core (typically fused silica) doped with a rare-earth element surrounded by a glass cladding with a lower refractive index (Figure 1b). Typical rare-earth dopants used in the core include ytterbium (Yb) ions and erbium (Er) ions. The rare-earth ions are excited or "pumped" by injecting light from an external pump source, typically a laser diode, into the fiber; the pump light is absorbed by the rare-earth ions. When the excited rare-earth ions drop back to the ground state, they emit light in specific wavelength bands; that is, the excited ions provide "optical gain." Coherent laser light is obtained either by seeding the fiber amplifier with a low-power laser (in a "master oscillator – power amplifier" configuration, as shown in Figure 1a) or by incorporating the gain fiber into a laser cavity (i.e., by providing feedback at the fiber ends using mirrors or fiber Bragg gratings – as illustrated in Figure 12). Yb-doped silica fibers provide gain in the ~1000–1200 nm region, and Er-doped silica fibers provide gain in the ~1500–1600 nm "eye-safe" region.

Mode-Filtered Fiber Amplifier

Product's Primary Function

The same functional description involving pump light, a gain medium, and output light applies to any solid-state laser. Fiber lasers represent an important step in the evolution of this class of devices, providing the unique advantages listed above.

The characteristic of diffraction-limited beam quality is key to understanding the significance of the Sandia/NRL mode-filtering invention and requires additional explanation. The theoretical limit for the spatial beam quality of a laser is known as the "diffraction limit." Diffraction-limited beams (also known as "Gaussian" or "single-mode*" beams) provide the lowest possible divergence and therefore the tightest possible focus. These characteristics are crucial for delivering high intensities (e.g., for materials processing) and small spot sizes (e.g., for micro-drilling), as well as for projecting a laser beam over a great distance with minimum spreading (e.g., for free-space communication and remote sensing). A so-called "single-mode" fiber supports only the "fundamental mode," which is diffraction limited; a single-mode fiber laser therefore produces a diffraction-limited output beam. By contrast, conventional multimode laser sources produce non-diffraction-limited output beams that are unstable, irreproducible, undesirably structured, and excessively divergent. These concepts are made more concrete in Figures 3 and 4, which show pictures of the various fiber modes and examples of single-mode and multimode beam quality.

How Mode-Filtered Fiber Amplifiers Work

The core of a single-mode fiber is relatively small (typically less than 10 microns in diameter), which limits both the energy storage and the power-handling capability of the fiber. Attempts to increase power by increasing core diameter were met with corresponding decreases in beam quality because larger-diameter cores operate on multiple modes – a fatal disadvantage in most applications. It was thus believed that fiber lasers were limited to low-power operation by fundamental physical properties of the fiber.

** "Modes" are the mathematical solutions to Maxwell's Equations for light propagating in the fiber, and a single-mode fiber allows only one solution (the diffraction-limited fundamental mode). Multimode fibers (and multimode lasers in general) permit many modes, most of which are not diffraction-limited, with a consequent degradation in beam quality.*

Mode-Filtered Fiber Amplifier

Product's Primary Function

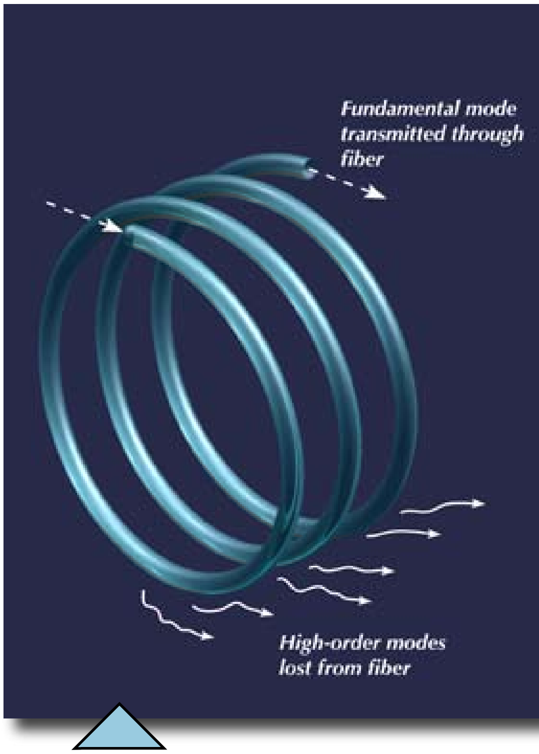


***Figure 2**: Illustration of the mode-filtering technique. In an appropriately coiled multimode fiber amplifier the undesired high-order modes are radiated from the side of the fiber along its entire length, whereas the desired fundamental mode is transmitted without significant attenuation. This "distributed spatial filtering" is accomplished by selecting a bend radius that permits propagation of the fundamental mode but introduces substantial bend loss for high-order modes. The figure is not drawn to scale. Typical diameters are ~0.25 mm for the fiber and ~50 mm for the coil, and the typical fiber length is ~5 m.*

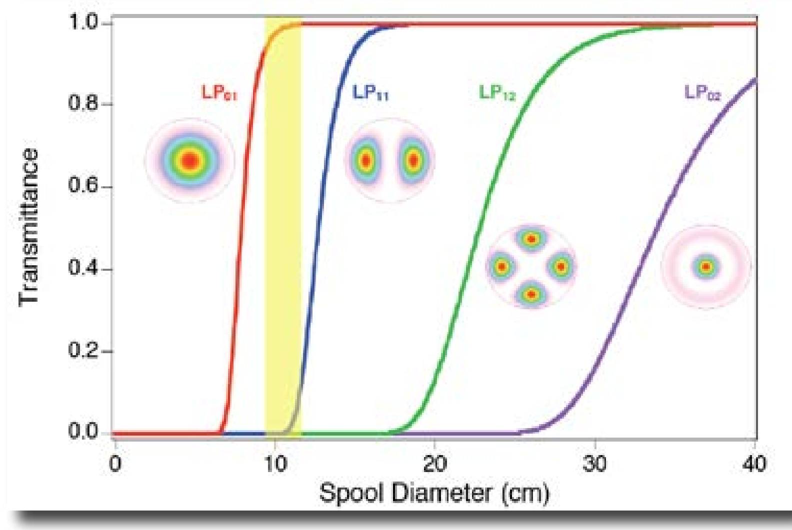
The Sandia/NRL Mode-Filtered Fiber Amplifier technology enables dramatic power scaling (by at least two orders of magnitude) of diffraction-limited fiber sources by allowing a highly multimode fiber to operate stably on a single mode. A key breakthrough was made in 2000, when Sandia/NRL researchers demonstrated that bend loss in a coiled fiber can act as a form of distributed spatial filtering to suppress all but the fundamental mode of a highly multimode (large core diameter) fiber amplifier – yielding single-mode, diffraction-limited operation with little or no loss in efficiency. By effectively decoupling core diameter from beam quality, the mode-filtering technique breaks the single-mode power limit on fiber lasers and amplifiers without sacrificing the other key advantages of fiber sources. At the time of its invention in 2000 and patent issuance in 2002, the Sandia/NRL approach shattered conventional wisdom, which held that multimode fibers could not produce high beam quality or, at best, were extremely sensitive to handling and bending.

The principle of operation of a Mode-Filtered Fiber Amplifier is shown qualitatively in Figure 2 and quantitatively in Figure 3. Sandia/NRL's coiling technique takes advantage of the fact that the desired fundamental mode is the least sensitive to bend loss (Figure 3); by strategically choosing the radius of curvature (spool diameter), it is possible to introduce very high loss for all high-order modes but negligible loss for the fundamental mode – thus filtering out the high-order modes and extracting all the light energy in the fundamental mode only. By suppressing propagation of high-order modes along the entire length of the fiber amplifier, the energy in the gain medium is left to be extracted in the desired fundamental mode. Thus high-power, single-mode operation is obtained without compromising any other performance characteristics.

MODE-FILTERED FIBER AMPLIFIER

Product's Primary Function

Figure 3: *Calculation showing the principle of operation for mode filtering. The graph plots the transmittance of some of the modes of a multimode fiber as a function of spool diameter. The fiber supports 14 modes, but only the lowest four modes are plotted. The spatial pattern of each mode is shown, with the circle denoting the fiber core (30 micron diameter). The desired fundamental mode (LP_{01}) is the least sensitive to bend loss. As indicated by the yellow bar, coiling the fiber on a spool with a diameter of 10-12 cm will provide high loss (low transmittance) for all undesired high-order modes while allowing the fundamental mode to be transmitted with very little attenuation. Note that the fundamental mode has a Gaussian spatial profile, providing diffraction-limited beam quality; the high-order modes have more structured profiles and are not diffraction-limited.*



The net result is shown in Figure 4, which displays photographs of the output face of a fiber amplifier when operated conventionally and when it is mode filtered using the Sandia/NRL technique; the dramatic improvement in beam quality is evident.

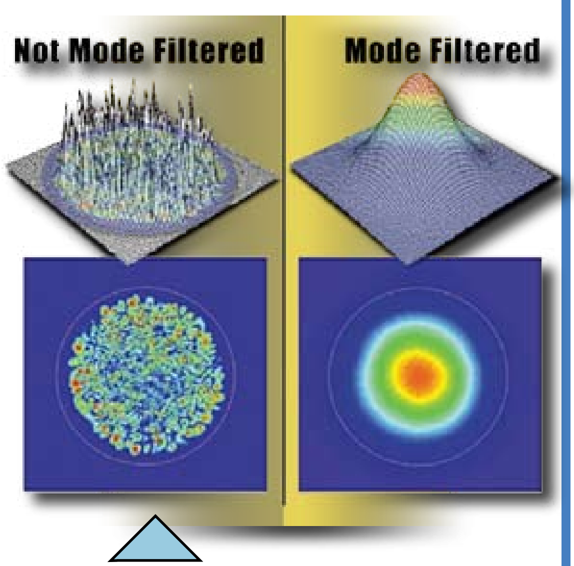


Figure 4: *Experimental comparison of the output beam from a fiber amplifier that is not mode filtered (left) vs. mode-filtered (right). The fiber supports 24 modes, and the core is denoted by the circles in the lower panels (25 micron diameter). The conventional unfiltered fiber amplifier produces a beam that is highly multimode, exhibiting undesirable structure and "hot spots" that vary with optical power level, vibration, time, handling of the fiber, etc., as the fiber modes compete for the optical gain; the beam is also highly divergent. In contrast, the mode-filtered beam is unstructured and stable, with diffraction-limited beam quality.*

Recognition of the Significance of the Sandia/NRL Advance

The significance of mode filtering was widely recognized in the laser field and even in the broader scientific community. Following publication in the premiere journal *Optics Letters*, the invention was extensively covered in the leading laser and optics trade journals (including *Laser Focus World* and *Photonics Online*) and was selected as an "example of the most significant recent research in optics and engineering," and one of "the 'hottest' topics in current optics research" by the Optical Society of America (*Optics and Photonics News*). It was also highlighted in the "Editor's Choice" column of the prestigious journal *Science*. More importantly, the technique was adopted by R&D groups worldwide. Breaking the single-mode power limit (along with the availability of more powerful pump diode sources) led to dramatic increases in attainable power from fiber lasers (Figure 5) – a trend that continues today.

Mode-Filtered Fiber Amplifier

Product's Primary Function

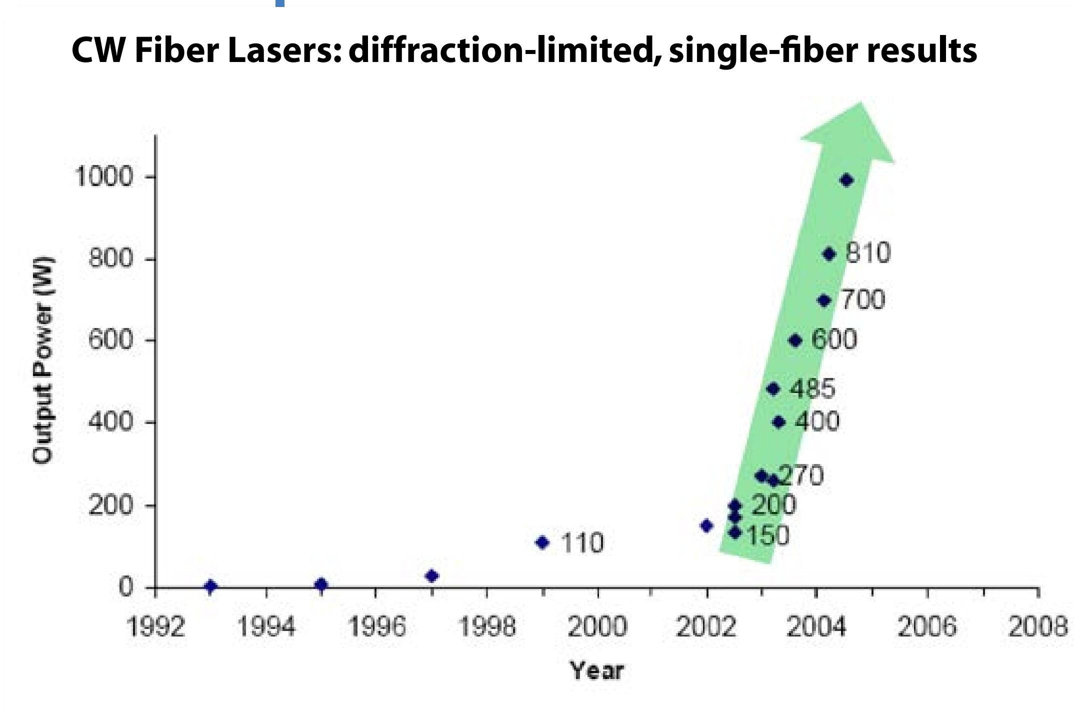


Figure 5: *Output power of diffraction-limited fiber lasers as a function of time. (Source: Nufern)*

Mode-Filtered Fiber Amplifier

Product's Competitors

As explained earlier under "Product Price," the Mode-Filtered Fiber Amplifier technology is licensed to users rather than manufactured by Sandia/NRL, and products competitive with the fibers, components, lasers, and laser systems that use it are broad and varied. Nevertheless, we provide a competitive comparison of mode-filtered fiber lasers vs. conventional laser systems in the next section.

Comparison Matrix

We first provide a general comparison of the performance characteristics of fiber lasers with competing laser technologies. We then compare the specifications of a commercial mode-filtered fiber laser with two commercial solid-state lasers in order to quantitatively illustrate the benefits of the Sandia/NRL invention.

Recently, manufacturers have prepared a number of comparisons of the performance of fiber lasers vs. high-power lasers traditionally used in materials processing (the laser application with the largest market share). Information that appeared in *Industrial Laser Solutions* (February 2006) summarizes the main attributes and illustrates the commanding lead now held by fiber lasers (Figure 6).

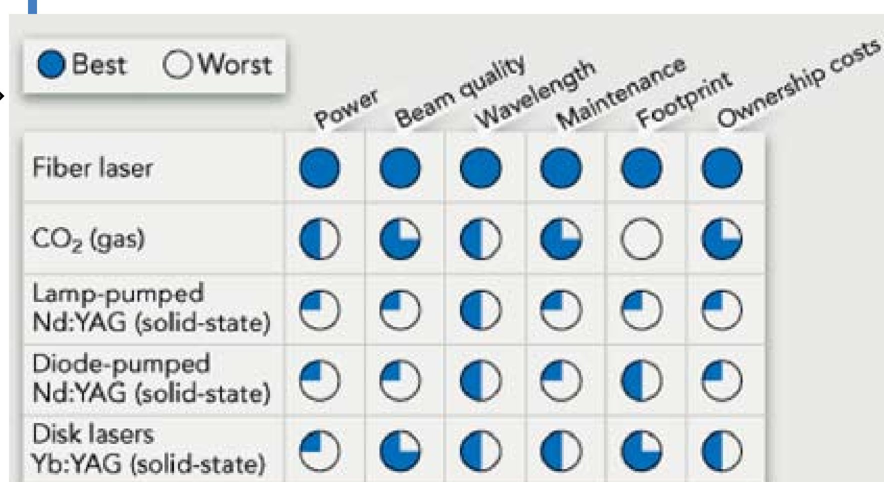


Figure 6: *Comparison of laser system attributes. (Source: High-power fiber lasers gain market share, Industrial Laser Solutions, February 2006, reprinted with permission.)*

Discussion of Advantages

Power & Footprint: As discrete lower-power units are coupled together, it is now possible to deliver >30 kiloWatts (kW) of optical power from a fiber laser, rivaling the output of traditional solid-state units. Owing to more compact packaging and lower cooling requirements, however, fiber lasers range from 3x smaller than disk lasers (their nearest competitor) to >20x smaller than Nd:YAG sources (the dominant solid-state laser technology); the advantage over gas lasers (e.g., CO_2) is

MODE-FILTERED FIBER AMPLIFIER

Comparison Matrix

even greater. A multi-kW fiber laser system can reduce floor space requirements (footprint) from 10 square meters to less than 1.5 square meters.

Beam Quality: The fundamental design of mode-filtered fiber lasers provides diffraction-limited beam quality (Figure 4), which does not degrade as power levels increase. The beam divergence of a fiber laser is one-tenth that of a CO_2 laser with a similar spot size, and it is significantly less than that of competing solid-state sources, even at power levels of <1 kW.

Wavelength Flexibility: The broad gain bandwidth of Yb-doped fiber allows lasing anywhere from 1000 to 1200 nm, and depending on the dopant used, fiber lasers can provide coverage across the spectrum from 1000 to 2000 nm. Furthermore, the infrared output of fiber lasers can be efficiently frequency-converted to other wavelengths, such as the ultraviolet (UV).

Maintenance & Operating Costs: Because there are no external optics to replace or align, and cooling requirements are minimal, fiber lasers require significantly less maintenance than conventional lasers. Now that high-power fiber-laser products have broken into manufacturing environments and have generated sufficient operating history for realistic comparisons to be made, it has been shown that operating costs are roughly a factor of two less than CO_2 lasers and nearly a factor of four less than other solid-state systems (Figure 7).

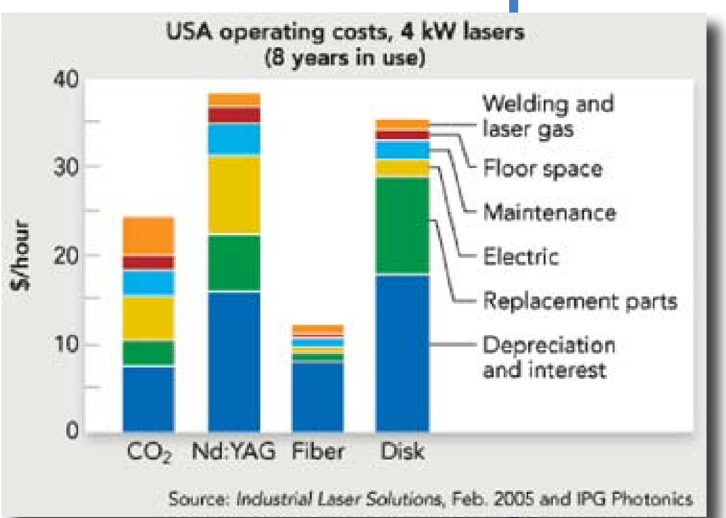


Figure 7: Comparison of operating costs for 4 kW lasers.
(Source: "High-power fiber lasers gain market share," Industrial Laser Solutions, February 2006, reprinted with permission.)

Mode-Filtered Fiber Amplifier

Comparison Matrix

Specific comparisons of a Nufern mode-filtered fiber laser to traditional solid-state lasers are given in Figure 8 and discussed below.

	Mode-Filtered Fiber Laser	Nd:YAG Laser	$Nd:YVO_4$ Laser
Manufacturer	**Nufern**	**Spectron**	**EdgeWave**
Output power (W)	180	40	200
Beam quality (M^2)	< 1.1	< 1.3	< 2
Operating mode	continuous wave	continuous wave	continuous wave
Pump source	diode lasers	diode lasers	diode lasers
Electrical power (W)	640	1000	1500
Electrical efficiency	28%	4%	13%
Volume, including power supply (cm^3)	6750	44,700	193,000 including chiller

Figure 8: *Comparison of a commercial mode-filtered fiber laser vs. two commercial solid-state lasers.*

Mode-Filtered Fiber Amplifier

How Our Product Improves upon Competitive Products or Technologies

For the purpose of this application, this section might be more appropriately labeled "How our invention improves on competitive products or technologies" because the Mode-Filtered Fiber Amplifier opened the door to a wide range of high-power fiber-laser products, allowing them to compete with numerous traditional solid-state laser systems. Fibers designed for mode filtering and licensed products incorporating mode-filtered fiber amplifiers form the basis of the business plan and product roadmap of co-applicants Nufern and Liekki, and three other companies recently signed licenses for the patent.

Figure 8 compares some of the key specifications of three commercial products: a mode-filtered fiber laser, a Nd:YAG laser, and a Nd:YVO_4 laser. The most important specifications of a laser system are application dependent, and a large number of optical and physical specifications are required to completely characterize the system. Furthermore, mode-filtered fiber amplifiers are incorporated into a wide range of products (continuous wave and pulsed, various power levels, various wavelengths, etc.). Any comparison thus provides only a "snapshot" of the technologies, but the data given in Figure 8 are representative and clearly illustrate the advantages of the mode-filtered fiber laser over previous solid-state laser technologies. Following a detailed comparison of these products in the two paragraphs below, we discuss the advantages of mode-filtered fiber lasers more generally.

As illustrated in Figure 8, the Nufern mode-filtered fiber laser delivers high power and simultaneously high beam quality (expressed here as the value M^2, where $M^2 = 1.0$ denotes the diffraction limit). The Spectron Nd:YAG laser was chosen for comparison because it provides near-diffraction-limited beam quality, although its power level is significantly lower (40 W vs. 180 W). Despite having nearly a factor of five higher output power, the mode-filtered fiber laser has a volume that is approximately one-sixth that of the Nd:YAG laser (i.e., the volume per Watt of output power is a factor of 30 better for the

How Our Product Improves upon Competitive Products or Technologies

mode-filtered fiber laser). Furthermore, the electrical efficiency of the mode-filtered fiber laser is dramatically higher – a factor of 7 improvement. Stated differently, despite consuming 1.6x the electrical power of the mode-filtered fiber laser, the Nd:YAG laser produces only 22% of the output power.

The Nd:YVO_4 laser was chosen for comparison because its output power is comparable to that of the mode-filtered fiber laser (although it does not achieve diffraction-limited beam quality) and because this bulk crystalline gain medium represents the latest advance in efficiency among diode-pumped solid-state lasers. Although the efficiency of the Nd:YVO_4 laser is 3x that of the Nd:YAG laser, the mode-filtered fiber laser is still a factor of 2 more efficient; furthermore the beam quality of the fiber laser is better by a factor of 2 at a comparable power level. (An exact comparison of size could not be given here because the power supply in the Nd:YVO_4 laser is integrated with the chiller. However, the laser head without the power supply is already twice as large as the mode-filtered fiber laser including the power supply, still highlighting the inherent advantage of the mode-filtered fiber laser.)

Compared to Nd:YAG lasers (the dominant solid-state laser source), specific benefits of mode-filtered fiber-laser technology include:

- A 5-fold increase in wall-plug efficiency (from typically <5% to ~25%).
- Elimination of external cooling – further reducing cost and bulk and increasing reliability.
- Stable, diffraction-limited beam quality that is insensitive to external perturbations or optical power level – allowing delivery of laser power with the smallest possible spot size.
- Ability to incorporate optical components monolithically into the fiber, thereby replacing free-space optics, eliminating alignment problems and increasing system ruggedness and reliability.

Mode-Filtered Fiber Amplifier

How Our Product Improves upon Competitive Products or Technologies

- Continuous tunability and wavelength agility for targeting specific molecules or absorption features.

Each of these benefits is discussed below.

High Electrical Efficiency

Simply stated, fiber lasers operate much more efficiently than conventional gas or solid-state lasers. The inherent efficiency of the fiber laser is unrivalled when compared to existing laser technologies (see Figure 9).

Laser	Optical-Optical Efficiency	Electrical Efficiency *
Lamp-pumped Nd:YAG	4 %	1 %
Diode-pumped Nd:YAG	40 %	16 %
Yb:YAG Disk	40 %	16 %
CO_2	N/A	10 %
Yb-doped fiber	75 %	30 %

* Electical efficiency = optical-optical efficiency x diode efficiency.

Figure 9: *Laser efficiency by type. The electrical efficiencies given in the table do not include the power requirements of the cooling system, which can be significant (e.g., the wall-plug efficiency of a diode-pumped Nd:YAG laser is typically <5%). (Source: Nufern)*

Low Waste Heat Generation

Figure 10 shows the energy levels associated with pumping and lasing in Nd:YAG and Yb-doped fiber lasers, illustrating that the "quantum defect" (difference between pump and emission energy) is smaller for the Yb-doped fiber laser so less heat is generated. Because less heat is generated per pump photon in a fiber laser, the lasing efficiency is correspondingly higher. In the example shown in Figure 10, the waste heat is reduced by a factor of 2.4 (from 24% to 10%).

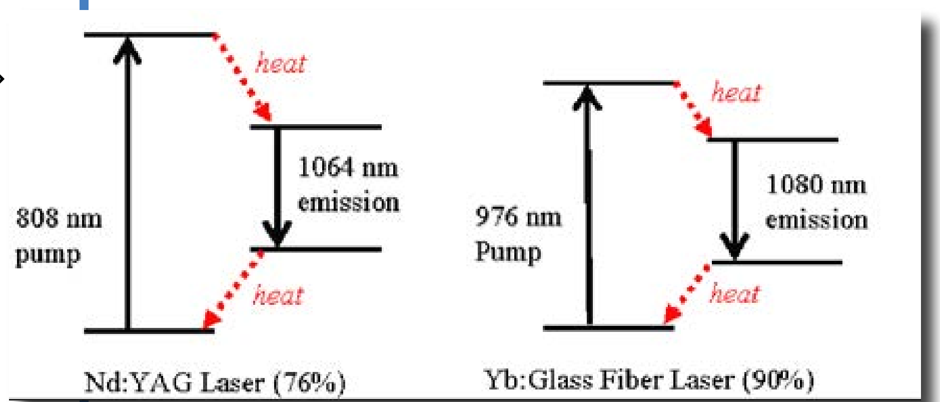


Figure 10: *Illustration of quantum efficiency. (Source: Nufern)*

Mode-Filtered Fiber Amplifier

How Our Product Improves upon Competitive Products or Technologies

Low Loss from the Gain Medium

With fiber lasers the pump absorption is distributed over the entire fiber length, and the pump light is never lost because it is confined and guided by total internal reflection in the fiber, with virtually no attenuation. In a typical solid-state laser, the pump and signal beams propagate and diffract freely rather than being confined to the gain medium. As a result, the gain that can be extracted from the system is relatively low (~10^1), and the net wall-plug efficiency (amount of electrical input energy that is ultimately converted to output light) is typically less than 5%. The vast majority of the input energy is thus not converted to light, but rather is wasted as heat energy that must be removed. In fiber lasers, the fiber gain medium acts as a "light pipe" that confines the pump and signal beams, effectively allowing more pump energy to be captured and converted. This unique feature of fiber lasers results in much higher gain (~10^4 – 10^5) and dramatically higher efficiency – as high as 40% wall-plug efficiency in laboratory systems demonstrated by Sandia/NRL researchers.

Stable Diffraction-Limited Beam Quality

The next important fundamental fiber property to consider is the ability of single-mode fibers to support only the fundamental mode (LP_{01}), resulting in a stable, diffraction-limited beam (see explanation presented earlier under "Product's Primary Function," especially Figure 4). In contrast, the free-space cavity design of a conventional laser system makes it difficult to achieve diffraction-limited beam quality – the beam quality is sensitive to alignment, vibration, temperature shifts, and optical power level, which contributes to unstable beam quality and variations in optical power. In essence, <u>the beam quality of a fiber laser is engineered into the gain medium</u>, whereas that of a conventional laser system is subject to the influence of a multitude of environmental and operational variables. Figure 4 shows a comparison of a single-mode, diffraction-limited beam and a multimode beam.

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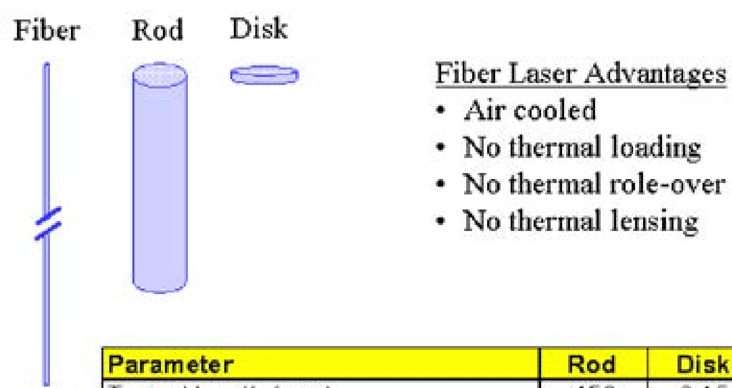
How Our Product Improves upon Competitive Products or Technologies

Facile Thermal Management

Another distinguishing feature of optical fibers is their high surface-area-to-volume ratio, resulting in facile heat removal — allowing fiber lasers to be air-cooled. In addition to efficiently confining light and producing desirable beam quality, optical fibers have a high surface-area-to-volume ratio, resulting in facile heat removal – allowing fiber lasers to be air-cooled. By contrast, the bulk gain media (e.g., Nd:YAG rods or Yb:YAG disks) employed in typical solid-state laser systems have relatively little surface area, making heat removal difficult, as illustrated in Figure 11.



Parameter	Rod	Disk	Fiber
Typical length (mm)	150	0.15	20,000
Outer diameter (mm)	9	10	0.125
Volume (mm3)	9,538	12	245
Cooled surface (mm2)	4,239	39	7,850
Cooled surface/ volume (1/mm)	**0.44**	**3.33**	**32**

Figure 11: *Fiber Laser Thermal Management. (Source: Nufern)*

Solid-state laser systems using bulk crystalline gain media must generally be intensively water-cooled, adding to system bulk, complexity, instability, and cost of operation. It should be noted that the fundamental inefficiency of conventional laser systems is greatly reinforced by the heat-removal problem – not only does a bulk medium produce far more heat than a fiber, but it is also significantly more difficult to remove that heat. Furthermore, thermal effects in the bulk gain medium can substantially degrade the beam quality, exacerbating the problems of these technologies.

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How Our Product Improves upon Competitive Products or Technologies

Monolithic System Architecture

Another attractive design feature of fibers is the ability to monolithically incorporate optical components directly into the fiber (such as lenses, mirrors, and gratings). This capability enables a hermetically sealed, alignment-free optical path, thereby increasing system reliability and ruggedness. By contrast, non-fiber systems direct a free-space beam through discrete optical components, which are subject to misalignment, contamination, and damage. Figure 12 illustrates how optical elements can be incorporated into the fiber to create a laser cavity (rather than the "master oscillator – power amplifier" configuration depicted in Figure 1a). Note also that the fiber is coiled at a strategically chosen diameter to effect mode filtering, as described earlier.

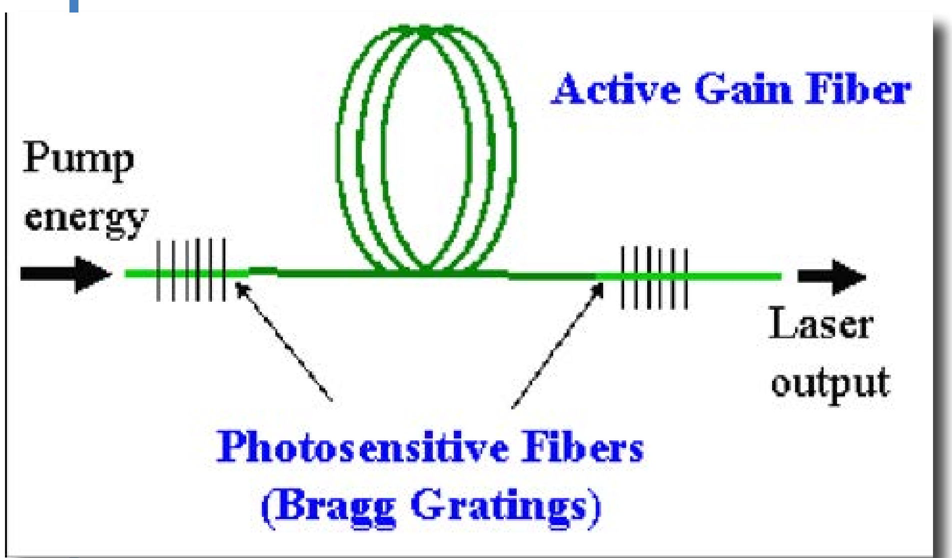

Figure 12: *High-power, mode-filtered fiber laser with optics embedded monolithically into the fiber.*

Broad Wavelength Coverage

Finally, gain media based on crystalline materials (e.g., YAG, YLF, YVO_4, etc.) are characterized by sharp optical transitions, which result in an output of discrete operating wavelengths. Rare-earth-doped fibers exhibit broad optical transitions, which result in a wide range of operating wavelengths and continuous tunability. The advantage of this wavelength agility and tunability is that the laser system can produce a range of desired wavelengths on demand, which is useful in a number of applications discussed below.

Mode-Filtered Fiber Amplifier

Principal Applications

Prior to 2002, the initial application of fiber lasers occurred in the telecommunications sector, where the primary advantage was that laser light could be amplified within an optical fiber. Traditionally, optical signals propagating in a fiber had to be removed from the fiber, converted to an electrical signal, amplified, converted back into an optical signal, and then re-injected into the communications fiber – an extremely cumbersome and inefficient process that had to be repeated at regular intervals as transmission degraded over distance. These traditional "repeaters" were replaced by "optical repeaters" based on fiber amplifiers, which directly amplify the optical signal in the fiber, thereby eliminating the electrical-optical conversion steps, electrical amplification, and re-injection of the amplified signal. This advance enabled the optical telecommunications revolution. Telecommunications provided the proving ground for fiber lasers, allowing the technology to demonstrate its practical advantages, to mature, and then to achieve the explosive growth that is the hallmark of a game-changing technology.

As noted earlier under "Product's Primary Function", fiber lasers were limited to low-power applications until the invention of the Mode-Filtered Fiber Amplifier by Sandia/NRL broke this barrier, providing the technology with entry into mainstream applications. Foremost among these is materials processing, where fiber lasers have already begun to capture a significant share of this >$1.7B market. Overall fiber laser sales exhibited a growth rate of 55 percent between 2005 and 2006 (to >$199M). (Source: "LASER MARKETPLACE 2007: Laser industry navigates its way back to profitability," *Laser Focus World,* January 2007.)

The workhorse of the solid-state commercial materials processing market is the Nd:YAG laser, operating at a wavelength of 1064 nm. Yb-doped fiber lasers currently offer a direct replacement at this wavelength. Fiber lasers have penetrated materials processing applications so quickly that it is expected that sales in this segment will comprise >$187M in

Mode-Filtered Fiber Amplifier

Principal Applications

2007, nearly 75% of all sales of fiber lasers. The dominant applications within materials processing are marking, cutting, cladding, drilling, and welding. Of these, the lowest-power application is laser marking, where fiber lasers already comprise >20% of the market and are displacing Nd:YAG units at an astonishing rate. Similar gains are expected in the remaining applications as available power levels continue to increase. Beyond these entry-level uses (where fiber lasers replace existing devices), continued development of pulsed fiber lasers – which deliver very short, intense bursts of light rather than a continuous stream of energy – is expected to open up more advanced application areas, such as semiconductor processing, high-aspect-ratio drilling, and processing of refractory materials. Note that the Sandia/NRL mode-filtering technique is equally enabling for both pulsed and continuous-wave fiber lasers, and the first two Sandia/NRL publications on the technology (Appendix B) demonstrated both modes of operation.

Mode-Filtered Fiber Amplifier

Other Applications

Owing to the wavelength agility cited earlier, fiber lasers are not limited to a few fundamental wavelengths. Sandia/NRL's mode-filtering technique has recently enabled generation of high peak powers (in excess of 1000 kW), which provide efficient conversion to other wavelengths – the ultraviolet (UV) region is of particular interest. The ability to deliver >10 Watts of UV power opens up applications in the electronics industry, especially semiconductor processing for manufacturing memory and computer chips (e.g., "link blowing" for maximizing yield in the production of semiconductor wafers), via drilling in circuit boards, electronics prototyping via subtractive board fabrication, and photolithography.

Compact, reliable laser sources are also in demand in the field of sensing – applications include:

- ranging and altimetry;
- three-dimensional mapping using laser radar (ladar);
- remote physical sensing, such as light detection and ranging (lidar);
- real-time, *in situ* and remote detection of chemical and biological compounds, (e.g., for pollution detection and prevention, and for process control in the energy and semiconductor industries); and
- medical diagnostics (e.g., breath analysis).

Mode-Filtered Fiber Amplifier

Summary

Despite great advances in spectral coverage and output power, high-power lasers remained predominantly laboratory tools that were bulky, fragile, inefficient, and/or provided poor beam quality. Massive investments (billions of dollars) in various laser technologies failed to overcome these limitations, and numerous potential applications of lasers were thus rendered impractical. Fiber lasers offered the possibility to unlock the full technological potential inherent in lasers and laser-based instruments, but fundamental limitations constrained this technology to low output powers and pulse energies. Sandia/NRL's Mode-Filtered Fiber Amplifier solved this long-standing problem, finally unlocking the full potential of fiber lasers.

Sandia/NRL's Mode-Filtered Fiber Amplifier technology represents a breakthrough that enables miniature, ultra-efficient, high-power laser sources that are revolutionizing the application of lasers to real-world problems. The Mode-Filtered Fiber Amplifier is an enabling technology that is elegantly simple but that shattered conventional wisdom by effectively decoupling fiber core size (power-generating capability) from beam quality.

Prior to its invention, operating a highly multimode fiber laser efficiently and stably on a single mode was considered a contradiction in terms. The solution – strategically coiling a fiber – is simple, contributes to compact packaging, and does not increase either the cost or the complexity of the laser system. It is this practical simplicity that makes the technology such a game-changer in so many application areas, and thus has led to the explosive growth described in this R&D 100 Award application.

The Sandia/NRL mode-filtering technique has been adopted by both academic and industrial R&D groups worldwide to achieve record-setting power levels from diffraction-limited fiber sources, and it has become the *de facto* standard for power scaling of pulsed and continuous-wave fiber lasers and

Mode-Filtered Fiber Amplifier

Summary

amplifiers. The technology has been licensed and commercialized by five companies in the U.S. and other countries. The invention is universally applicable across many fiber types and touches virtually every application area where lasers may be used.

Mode-Filtered Fiber Amplifier

Contact Person to Handle All Arrangements on Exhibits, Banquets, and Publicity

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MODE-FILTERED FIBER AMPLIFIER

Appendix A: Front-Page Patent Image

(12) **United States Patent**
Koplow et al.

(10) **Patent No.: US 6,496,301 B1**
(45) **Date of Patent: Dec. 17, 2002**

(54) **HELICAL FIBER AMPLIFIER**

(75) Inventors: **Jeffrey P. Koplow**, Washington, DC (US); **Dahy Kliner**, San Ramon, CA (US); **Lew Goldberg**, Fairfax, VA (US)

(73) Assignee: **The United States of America as represented by the Secretary of the Navy**, Washington, DC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/523,215**

(22) Filed: **Mar. 10, 2000**

(51) **Int. Cl.**[7] **G02B 6/120**; H01S 3/07

(52) **U.S. Cl.** **359/337**; 359/337.1; 359/337.2; 359/341.1; 385/104

(58) **Field of Search** 357/337, 341, 357/885, 337.1, 337.2, 341.1; 385/1, 104

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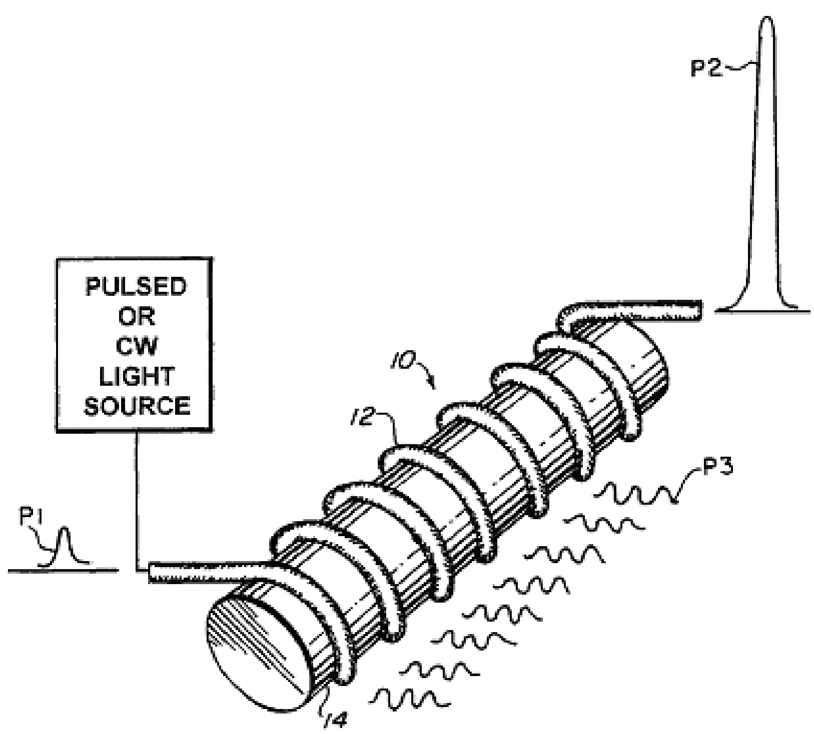
* cited by examiner

Primary Examiner—Nelson Moskowitz
(74) *Attorney, Agent, or Firm*—John J. Karasek; Dorothy I. Becker

(57) **ABSTRACT**

A multi-mode gain fiber is provided which affords substantial improvements in the maximum pulse energy, peak power handling capabilities, average output power, and/or pumping efficiency of fiber amplifier and laser sources while maintaining good beam quality (comparable to that of a conventional single-mode fiber source). These benefits are realized by coiling the multimode gain fiber to induce significant bend loss for all but the lowest-order mode(s).

20 Claims, 9 Drawing Sheets



Mode-Filtered Fiber Amplifier

Key papers and articles are listed below. A front-page image from each source is supplied on the pages following the list.

Selected archival papers written by the team:

- "**Single-mode operation of a coiled multimode fiber amplifier**," Koplow, JP; Kliner, DAV; Goldberg, L; in *Optics Letters*; April 1, 2000; v.25, no.7, p.442-444.
- "**Diffraction-limited, 300-kW peak-power pulses from a coiled multimode fiber amplifier**," Di Teodoro, F; Koplow, JP; Moore, SW; Kliner, DAV; in *Optics Letters*; April 1, 2002; v.27, no.7, p.518-520.
- "**High-Peak-Power (>1.2 MW) Pulsed Fiber Amplifier,**" Farrow, RL; Kliner, DAV; Schrader, P.E.; Hoops, AA; Moore, SW; Hadley, G R and Schmitt, RL; Proc. SPIE Vol. 6102,61020L, *Fiber Lasers III: Technology, Systems, and Applications;* February 2006.

Technical articles written by the team:

- "**Single-transverse-mode operation of a coiled multimode fiber amplifier**," Koplow, JP; Kliner, DAV; Goldberg, L; in *Optics and Photonics News*; December 2000; v.11, no.12, p.21-22.
- "**Fiber Laser Technology Reels in High Power Results**," Kliner, DAV Koplow, JP and Di Teodoro, F; *oe magazine*, January 2004. [Available at http://oemagazine.com/fromthemagazine/jan04/tutorial.html]

Articles recognizing the invention of the Mode-Filtered Fiber Amplifier:

- "**Optics in 2000**," *Optics and Photonics News*, issue 11, no 12, p. 16, December 2000.
- "**CLEO 2000: Coiled fiber amplifiers produce high power single-mode pulses**," Yvonne Carts-Powell, *Photonics Online*, May 12, 2000. [Available at http://www.photonicsonline.com/content/news/article.asp?docid={988b6850-275d-11d4-8c3c-009027de0829}]
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- "**Fiber Laser Technology Review**," a webcast presentation by Andrew Held of Nufern, May 17, 2006. [This webcast – audio and slides -- may be accessed from http://www.smalltimes.com/webcast/display_webcast.cfm?id=200]

"**Single-mode operation of a coiled multimode fiber amplifier**," *Optics Letters;* April 1 2000; v.25, no.7, p.442-444.

442 OPTICS LETTERS / Vol. 25, No. 7 / April 1, 2000

Single-mode operation of a coiled multimode fiber amplifier

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Received November 3, 1999

We report a new approach to obtaining single-transverse-mode operation of a multimode fiber amplifier in which the gain fiber is coiled to induce significant bend loss for all but the lowest-order mode. We demonstrated this method by constructing a coiled amplifier using Yb-doped, double-clad fiber with a core diameter of 25 μm and a numerical aperture of ~0.1 ($V \approx 7.4$). When the amplifier was operated as an amplified-spontaneous-emission source, the output beam had an M^2 value of 1.09 ± 0.09; when seeded at 1064 nm, the slope efficiency was similar to that of an uncoiled amplifier. This technique will permit scaling of pulsed fiber lasers and amplifiers to significantly higher pulse energies and peak powers and cw fiber sources to higher average powers while maintaining excellent beam quality. © 2000 Optical Society of America

OCIS codes: 060.2320, 140.3510, 140.4480, 140.3570.

Single-mode (SM), rare-earth-doped fiber lasers and amplifiers are finding widespread use in applications that require compact, rugged optical sources with diffraction-limited beam quality. The advent of double-clad fibers has allowed these sources to be scaled to average powers of >100 W.[1] For applications that require high-energy pulses, however, use of fiber-based systems has been limited by the relatively low pulse energies available compared with those of bulk lasers. This pulse-energy limitation arises from low energy storage and the onset of nonlinear processes in the fiber. The energy-storage capacity of a fiber is determined by amplified spontaneous emission (ASE), which limits the maximum population inversion.[2] The most important nonlinear processes that limit the pulse energy and peak power are stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS).[3] For cw applications that require narrow linewidth, the maximum power is limited by SBS.

Two approaches to overcoming these limitations have been reported. Taverner and colleagues developed large-mode-area, Er-doped SM fibers with numerical apertures (NA's) of 0.066–0.08 and core diameters of 14–17 μm ($V = 2.2$–2.4).[4,5] Decreasing the NA (relative to standard telecommunication values of ~0.15) allows the core size to be increased while maintaining SM operation. The resultant increased mode-field area raises the threshold for nonlinear processes. In addition, the lower NA reduces the fraction of spontaneous emission captured by the fiber, thereby increasing energy storage.[6] Several groups have used multimode (MM) fiber amplifiers and have obtained various levels of suppression of high-order modes by adjusting fiber index and dopant distributions,[7,8] cavity configurations,[9,10] or launch conditions of the seed beam.[11–15] In all these approaches, increasing the rare-earth-dopant concentration permits the use of shorter fibers, which proportionally increases the threshold power for SRS and SBS.

We report a new approach to obtaining SM operation of a laser or amplifier using MM fiber. By wrapping the gain fiber around a cylindrical mandrel whose radius is chosen to provide low loss for the fundamental mode (LP_{01}) and high loss for LP_{11} and the other high-order modes, bend loss can be used as a form of distributed spatial filtering. This technique exploits the fact that LP_{01} is the least sensitive to bend loss and that, for all modes, the bend-loss attenuation coefficient (α, in decibels per meter) depends exponentially on the radius of curvature.[16] Using bend loss to discriminate against high-order modes allows the core diameter to be increased significantly beyond the SM limit (i.e., the restriction $V < 2.405$ is eliminated), thereby allowing fiber lasers and amplifiers to be scaled up to much higher peak and average powers. Furthermore, for a double-clad fiber with a given inner-cladding area, the pump absorption coefficient increases quadratically with core diameter, permitting the use of shorter lengths of fiber; alternatively, increasing both the core and inner-cladding sizes permits the use of larger, higher-power pump sources without the need for prohibitively long fibers. Although this approach is fully compatible with (and may be extended by) other methods for suppressing modes above LP_{01}, it does not require that the launch conditions and mode quality of the seed beam be carefully matched to LP_{01}, nor does it require exotic fiber designs, to obtain diffraction-limited performance.

The mode-filtering effect that is the basis of the coiled amplifier is shown in Fig. 1. Following the analysis of Marcuse,[16] we calculated the attenuation for LP_{11} ($\gamma_{11} = \alpha_{11}L$, where L is the fiber length) as a function of fiber core diameter for specified values of LP_{01} attenuation (γ_{01}). This calculation applies to a step-index fiber with a NA of 0.08 (a typical value for a low-NA fiber) and $L = 10$ m. The attenuation coefficients for modes of order higher than LP_{11} are larger than α_{11}, and these modes will therefore be even more

0146-9592/00/070442-03$15.00/0

"**Diffraction-limited, 300-kW peak-power pulses from a coiled multimode fiber amplifier**," *Optics Letters;* April 1 2002; v.27, no.7, p.518-520.

518 OPTICS LETTERS / Vol. 27, No. 7 / April 1, 2002

Diffraction-limited, 300-kW peak-power pulses from a coiled multimode fiber amplifier

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Received October 26, 2001

We report a multimode, double-clad, Yb-doped fiber amplifier that produces diffraction-limited, 0.8-ns pulses with energies of 255 μJ and peak powers in excess of 300 kW at a repetition rate of ~8 kHz. Single-transverse-mode operation was obtained by bend-loss-induced mode filtering of the gain fiber. © 2002 Optical Society of America

OCIS codes: 060.2320, 140.3510, 140.4480, 140.3570, 060.4370.

Single-mode (SM) rare-earth-doped fiber lasers and amplifiers are compact, rugged optical sources with diffraction-limited beam quality, but their use for pulsed applications is hampered by the low pulse energies available compared with those for bulk solid-state lasers. Two factors limit pulse energy: low energy storage owing to amplified spontaneous emission[1] and the onset of nonlinear processes,[2] such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The simplest way to overcome both limiting factors is to increase the fiber core diameter (d_{core}), which results in a smaller fraction of spontaneous emission being captured by the core in the fundamental mode and in a higher threshold power for SBS and SRS. In addition, as the pump absorption coefficient increases quadratically with d_{core} for a given inner cladding diameter, shorter lengths of fiber can be used, which proportionally raises the threshold power for SBS and SRS.

Taverner *et al.*[3] obtained SM operation of an Er-doped fiber amplifier with d_{core} of 17 μm by lowering the numerical aperture to 0.066–0.08. An upper limit to the value of d_{core} in SM fibers is imposed by the unacceptably high bending sensitivity at low N.A. Alternatively, several groups used multimode (MM) fibers in which they suppressed the propagation of transverse modes other than the fundamental (LP_{01}) mode by suitably designing the fiber index and dopant profiles,[4,5] by introducing special cavity configurations,[6] by tapering the fiber ends,[7] or by adjusting the seed launch conditions.[8] Koplow *et al.* showed that one can recover diffraction-limited beam quality by coiling a MM fiber to induce substantial bend loss for all transverse modes except LP_{01}.[9] Important practical advantages of this technique are that it is easy to implement, does not require the seed mode quality to be carefully matched to LP_{01}, and does not rely on complex fiber designs.

A great deal of research has been devoted to continuous-wave and mode-locked fiber lasers, and both have proved useful in a variety of applications. The focus of the present study is on nanosecond-duration pulsed fiber sources. The most commonly used nanosecond sources are Q-switched solid-state lasers with pulse durations of 0.5–20 ns. These lasers are used in applications that have one or more of the following requirements: high peak power (e.g., nonlinear frequency conversion), narrow linewidth (e.g., laser spectroscopy), and large pulse energy (e.g., lidar). For transform-limited pulses with durations in excess of ~10 ns, the threshold power for SBS in a fiber is more than 2 orders of magnitude lower than that for SRS,[2] and SBS imposes severe limitations on the peak power that can be transmitted through the gain fiber. As the pulse duration is decreased below 10 ns, the threshold for SBS increases steeply because (1) the linewidth of a transform-limited pulse exceeds the Brillouin gain bandwidth (typically ~50 MHz), (2) the spatial overlap of the optical pulse and the counterpropagating SBS wave becomes shorter than the length of the fiber amplifier, and (3) the highest peak powers are not generated until the pulse has propagated through most of the amplifier (because of the approximately exponential growth of the pulse along the fiber, the effective interaction length for SBS is inversely proportional to the gain per unit length of the amplifier). For transform-limited pulses of less than ~1-ns duration, SRS thus becomes the dominant nonlinear process. Any further decrease in pulse duration does not necessarily result in higher peak powers and is undesirable if the pulse energy is to be maximized or the spectral linewidth is to be minimized.

In this Letter we report the first realization of a coiled MM fiber amplifier for pulsed operation with SM output. We used 7.0 m of the Yb-doped, double-clad (DC) fiber described in Ref. 10. The core diameter and N.A. were 25 μm and ~0.10, respectively, which correspond to $V \approx 7.4$ at 1064 nm. For bend-loss mode filtering we used two cylindrical spools of 1.67-cm diameter, each wrapped with 3.5 m of DC fiber. The spools were oriented orthogonally

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MODE-FILTERED FIBER AMPLIFIER

"**High-Peak-Power (>1.2 MW) Pulsed Fiber Amplifier**," *Proc. SPIE Vol. 6102, 61020L, Fiber Lasers III: Technology, Systems, and Applications*; February 2006.

High-peak-power (>1.2 MW) pulsed fiber amplifier

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ABSTRACT

We report results from Yb-doped fiber amplifiers seeded with two microchip lasers having 0.38-ns and 2.3-ns pulse durations. The shorter duration seed resulted in output pulses with a peak power of >1.2 MW and pulse energy of 0.67 mJ. Peak power was limited by nonlinear processes that caused breakup and broadening of the pulse envelope as the pump power increased. The 2.3-ns duration seed laser resulted in output pulses with a peak power of >300 kW and pulse energy of >1.1 mJ. Pulse energies were limited by the onset of stimulated Brillouin scattering and ultimately by internal optical damage (fluences in excess of 400 J/cm^2 were generated). In both experiments, nearly diffraction-limited beam profiles were obtained, with M^2 values of <1.2. Preliminary results of a pulse-amplification model are in excellent agreement with the experimental results of the amplifiers operating in the low-to-moderate gain-depletion regime.

Keywords: fiber amplifier, pulsed fiber amplifier, high-peak-power fiber amplifier, bend loss, mode filtering, large-mode-area amplifier, Yb

1. INTRODUCTION

Numerous applications of lasers require optical pulses with high beam quality, milliJoule pulse energies, and nanosecond pulse durations, including materials processing, remote sensing (chemical and physical), and nonlinear frequency conversion. These applications have traditionally employed diode-pumped solid-state lasers, but recent advances in rare-earth-doped fiber lasers offer the possibility of meeting the requirements with smaller, lighter, more efficient, and more reliable fiber-based sources. In particular, bend-loss-induced mode filtering has allowed pulsed fiber lasers and amplifiers to be scaled to mJ pulse energies and MW peak powers while maintaining diffraction-limited beam quality. This method permits the use of multimode fibers with large core diameters, which are able to generate higher pulse energies and peak powers, by making use of the strong increase in bend loss with mode order.[1] A spooling diameter is chosen such that the LP_{01} fundamental mode has an acceptable (often negligible) attenuation, while the higher order modes are nearly eliminated.[2] Using this technique, Di Teodoro and coworkers[3] obtained diffraction-limited, 0.8-ns duration pulses with energies >255 µJ and peak powers >305 kW from a single 25-µm core-diameter Yb-doped, double-clad (DC) fiber. Although not diffraction limited (M^2 = 6.5), Cheng and coworkers[4] obtained a record peak power of 2.4 MW from 4-ns duration pulses with energies of 9.6 mJ, using a multi-stage setup ending with a mode-filtered 200-µm diameter Yb-doped fiber.

Torruellas and coworkers[5] have developed custom-fabricated, non-step-index fibers designed to support a large area, flattened mode with an effective area of 2075 µm^2. In a two-stage amplifier setup, they obtained 1.5-MW peak power, 25-GHz linewidth, pulses with energies up to 0.75 mJ, pulse durations of <0.5 ns, and $M^2 < 2$.

Another approach providing mode selection in large core-diameter fibers uses microstructured materials to create so-called holey fibers that inherently support only the fundamental mode. Di Teodoro and Brooks[6] recently reported diffraction-limited, 0.45-ns duration pulses from a holey fiber with an LP_{01} mode diameter of 33.5 µm. Peak powers of >1.1 MW with pulse energies of 540 µJ were obtained; some self-

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Appendix B: Front-Page Papers and Articles

"**Single-transverse-mode operation of a coiled multimode fiber amplifier**," *Optics and Photonics News*; December 2000; v.11, no.12, p.21-22.

Optics in 2000

Interference Imaging For Aspheric Surface Testing

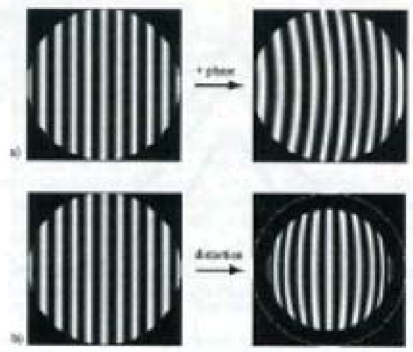
By Paul E. Murphy, Thomas G. Brown, and Duncan T. Moore

Aspheric optical surfaces provide superior performance in the design of optical systems. Yet their broad application requires effective design, fabrication, and metrology. Powerful computers and algorithms allow use of aspheres in lens design software. Modern computer-controlled fabrication processes automatically generate aspheres, and deterministic polishing processes, such as magnetorheological finishing (MRF), finish the part.[1] The lack of flexible metrology, however, remains a major bottleneck to many cost-effective solutions. Null interferometry is an accurate tool for the testing of spherical surfaces. Extending this capability to aspheres, however, requires the design and fabrication of special null optics.

Testing aspheres in a null configuration is both inflexible and expensive, thereby limiting their use in practical system designs. The ability to measure an asphere without corrective optics would alleviate this problem. Such non-null tests, however, have intrinsic barriers to implementation. Two effects in particular stifle non-null interferometry: the density of the interference fringes and the failure of the common-path assumption. Of these two problems, the common-path failure is more pervasive, leading to retrace errors that introduce bias into the measurement. Empirical techniques demonstrate some capability of predicting (and thus removing) such errors but do not indicate whether another interferometer design might perform better.[2,3]

A more fundamental model gives insight into the effects that drive the interference imaging errors. Huang analytically postulated the effects of some aberrations in a Fizeau interferometer and illustrated distortion experimentally.[4] We explore the effect of coherent fringe imaging in detail under a geometrical-optics framework.[5] One key contribution is a general expression for interference imaging errors as a function of the imaging system's conventional parameters. The errors are subclassified into phase and mapping and are predicted from the wavefront aberration of the imaging system. Figures 1(a) and 1(b) illustrate the concept of phase and mapping errors. Our method predicts these errors from the imaging system parameters and the slope departure of the test wavefront (from the reference). Analytic results are obtained through aberration theory, presenting a powerful framework for describing non-null interference. Experiments on tilted and defocused spheres by use of a single-element imager demonstrated agreement with the theory to better than tenth-wave on some forty waves of defocus.[6]

General prediction of interferometer errors has several important applications. The amount of measurement error can be quickly estimated. Better still, the errors can be removed, although uncertainties in the imaging aberration values limit such a correction. Unknown tilt and decentration of the individual imaging elements introduce systematic errors in the aberrations, although even this problem can potentially be addressed with system calibration. Another application of the analysis is in the design of interferometers. Conventional analysis methods typically apply only to a particular interferometer, and thus comparison between designs is quite tedious. The methods presented in this research are based on the conventional aberration characteristics of the interferometer imaging system. Inasmuch as the imaging error predictions are general, they can be optimized. The manifold tools of lens design become available to non-null interferometer design, rather than relying on ad hoc methods.



Interference Imaging Figure 1. Pictorial examples of phase and mapping errors. a) A phase error with quadratic dependence on part position. b) The mapping error induced by 20% third-order barrel distortion.

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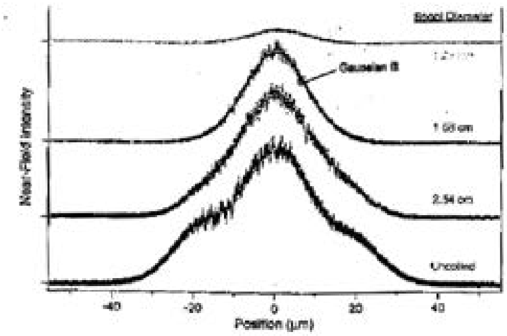
LASERS

Single-Transverse-Mode Operation of a Coiled Multimode Fiber Amplifier

By Jeffrey P. Koplow, Dahv A. V. Kliner, and Lew Goldberg

Single-mode (SM), rare-earth-doped fiber lasers and amplifiers are widely used in telecommunications and other applications requiring compact, rugged optical sources with diffraction-limited beam quality. For appli-

"**Single-transverse-mode operation of a coiled multimode fiber amplifier**," *Optics and Photonics News*; December 2000; v.11, no.12, p.21-22.



Multimode Fiber Amplifier Figure 1. Near-field intensity distribution of ASE from MM amplifier for the indicated spool diameters.

cations requiring high-peak-power pulses or narrow linewidth, however, use of fiber-based systems has been limited by the relatively low energy-storage capacity of SM fibers and by the onset of nonlinear processes in the fiber. These problems can be mitigated by increasing the core diameter of the fiber, but eventually the fiber will support higher-order modes; such multimode (MM) fibers are generally characterized by poor beam quality, which restricts their use in applications such as nonlinear frequency conversion, pumping of optical parametric oscillators and amplifiers, lidar, and materials processing.

Two approaches to overcoming these limitations have been reported. Taverner *et al.* developed erbium-doped fibers with low numerical apertures, which allowed the core size to be increased while maintaining SM operation.[1] Alternatively, several groups using MM fiber amplifiers have obtained varying levels of suppression of high-order modes by adjusting the launch conditions of the seed beam[2] or the fiber refractive-index and rare-earth-dopant distributions.[3]

In a recent paper,[4] researchers at the Naval Research Laboratory and Sandia National Laboratories reported a new approach to obtaining SM operation of a laser or amplifier employing MM fiber. This technique exploits the fact that the fundamental mode (LP_{01}) is least sensitive to bend loss when the fiber is coiled. Thus, by wrapping a gain fiber around a cylindrical mandrel whose radius is chosen to provide low loss for LP_{01} and high loss for higher-order modes, bend loss can be used as a form of distributed spatial filtering to suppress all but the fundamental mode of a MM fiber amplifier.

The technique was demonstrated by construction of an ytterbium-doped fiber amplifier using MM fiber with a core diameter of 25 µm (more than three times the diameter of a comparable SM fiber). The fiber was end pumped with 3.9 W at 975 nm, and the copropagating amplified-spontaneous-emission (ASE) power and near-field spatial profile (intensity versus position at the fiber output face) were measured to determine the optimum spool diameter (ASE uniformly excites all modes of the MM fiber). Figure 1 shows the near-field spatial profile for several spool diameters and demonstrates the suppression of higher-order modes before the onset of significant loss for LP_{01} (whose spatial profile is nearly Gaussian). Measurements with a 1.58-cm spool diameter demonstrated a rigorously diffraction-limited output beam and, when the amplifier was seeded at 1064 nm, a slope efficiency that was nearly unchanged from that of an uncoiled amplifier. A maximum output power of 4.1 W was obtained with 11 W of pump power.

This new approach does not increase system complexity, is inexpensive to implement, and is compatible with (and may be extended by) other methods for suppressing modes above LP_{01}. It will allow for scaling of pulsed fiber lasers and amplifiers to significantly higher pulse energies and peak powers and cw fiber sources to higher average powers while maintaining excellent beam quality.

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4. J. P. Koplow, D. A. V. Kliner, and L. Goldberg, "Single-mode operation of a coiled multimode fiber amplifier," Opt. Lett. **25**, 442-4 (2000).

Gain Switching and Active Mode Locking Of Mid-Infrared Quantum Cascade Lasers

By Roberto Paiella, Federico Capasso, Claire Gmachl, Clyde G. Bethea, Harold Y. Hwang, Deborah L. Sivco, James N. Baillargeon, Albert L. Hutchinson, Alfred Y. Cho, and H. C. Liu

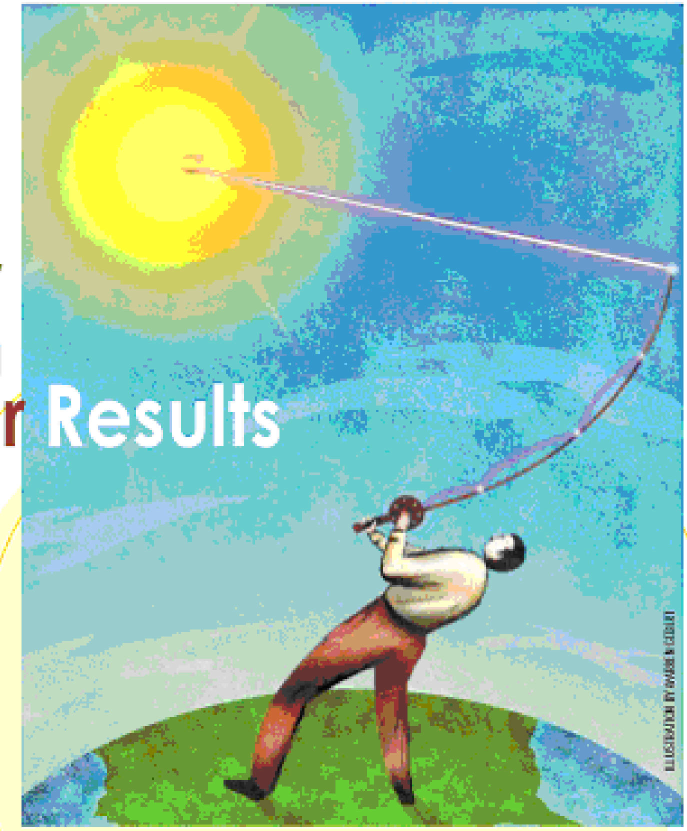
Quantum cascade (QC) lasers[1] are light sources based on optical transitions between quantized states of the conduction band in semiconductor nanostructures. These devices emit in the mid-infrared spectral region, which is known as the molecular fingerprint region, because many chemical and biological species have their telltale absorption features at these wavelengths. This spectral range is characterized by the lack of convenient laser sources of ultrashort pulses. On the other hand, these sources would be quite desirable for several applications, ranging from time-resolved spectroscopy to coherent control. Recently, we demonstrated the generation of picosecond mid-infrared pulses with gain-switched and actively mode-locked QC lasers.

Gain switching consists of driving an injection laser, biased below threshold, with short electrical pulses to generate even shorter optical pulses. In particular, we used a commercial step-recovery diode (comb generator) that produced voltage pulses of approximately 90 ps, at a repetition rate of 100 MHz to gain switch several QC lasers, properly packaged for high-speed operation.[2] A typical output pulse from an 8-µm device is shown in the left-hand panel of the figure, as measured with a high-speed quantum-well infrared photodetector (QWIP).[3] A pulse duration of 89 ps is directly obtained from this trace; accounting for the finite response time

"**Fiber Laser Technology Reels in High Power Results**," *oe magazine*, January 2004.

TUTORIAL

Fiber Laser Technology Reels in High Power Results



By Dahv Kliner, Sandia National Laboratories; and Jeffrey Koplow, Fabio Di Teodoro, and Sean Moore, Naval Research Laboratory

By using bending loss to suppress higher-order modes in multimode fiber, researchers have achieved high power output from fiber lasers.

Single-mode, rare-earth-doped fiber lasers and amplifiers are widely used in telecommunications and other applications requiring compact, rugged optical sources with high beam quality. Fiber sources provide high electrical-to-optical efficiency (up to 39% for Yb-doped fiber amplifiers), small-signal gains as high as 10^5, and low-threshold operation. The devices can achieve diffraction-limited beam quality ($M^2 = 1$) that is defined by the refractive-index profile of the fiber and is thus insensitive to thermal or mechanical fluctuations or optical power level. The glass host broadens the optical transitions in the rare-earth ion dopants, yielding continuous tunability; moreover, the variety of possible rare-earth dopants such as Yb, Er, and Tm yields broad wavelength coverage in the near-IR spectral region. Fiber lasers can be diode pumped and further offer low heat dissipation and facile heat removal (high surface-area-to-volume ratio) and room-temperature operation. They also require no consumables other than electrical power.

Until recently, fiber sources had been limited to relatively low output powers, preventing their use in a number of important applications that demand high average power, peak power, and/or pulse energy. Recent advances, however, have enabled dramatic power scaling of continuous-wave (CW) and pulsed fiber sources, bringing the benefits of this technology to a wide range of applications previously dominated by other laser systems: materials processing, lidar, and nonlinear frequency conversion, for example. These developments have led to a surge of interest in fiber-based laser systems for both industrial and military use.

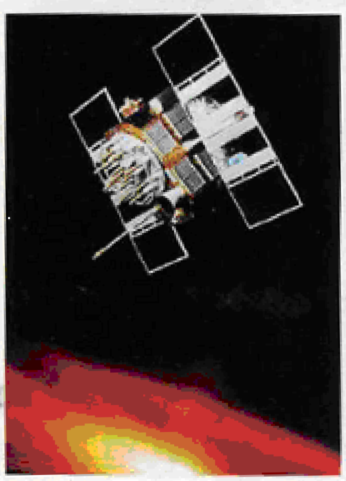
Power Limitations

An idealized step-index fiber has uniform refractive indices in both the core (n_{core}) and the cladding (n_{clad}). Such a fiber will guide only the fundamental mode LP_{01} if the normalized frequency (V) is ≤ 2.4, where $V = \pi\, d_{core}\, NA_{core} / \lambda$, d_{core} is the core diameter, λ is the wavelength, and the numerical aperture NA_{core} is given by $\sqrt{n_{core}^2 - n_{clad}^2}$. Typical singlemode fibers operating in the near-IR spectral region have d_{core} values of 6 to 8 µm and NA values of about 0.15.

High-power fiber sources incorporate double-clad fiber (see figure 1), in which the rare-earth-doped core is surrounded by a much larger and higher-NA inner cladding. Light from high-power multimode pump

"**Optics in 2000**," *Optics and Photonics News*, issue 11, no 12, p. 16, December 2000.

Guest Editor: Bob D. Guenther
Physics Department, Duke University



Examples of the most significant recent research in optics and engineering are published each year in the December issue of OPN. This issue is comprised of short descriptions of the "hottest" topics in current optics research. Selection criteria applied to submissions are as follows:

- the accomplishments described must have been published in a refereed journal in the year prior to publication in OPN;
- the work must be illustrated in a clear, concise manner, comprehensible to the at-large optics community;
- the topical area as a whole must be described, and the importance of the research must be detailed.

There are no requirements in the selection process for inclusion of specific topical areas. When a large number of submissions are received for a specific area, this is taken as evidence that the topic has been fertile ground for activity and research over the course of the preceding year. OPN strives to ensure that engineering, science, and technology are all represented. The number of papers accepted overall is limited by space.

With 33 papers accepted, 2000 has proven to be another successful year. OPN and OSA would like to thank the hundreds of researchers from all over the world who submitted summaries to Optics in 2000.

Appendix B: Front-Page Papers and Articles

"**CLEO 2000: Coiled fiber amplifiers produce high power single-mode pulses**," *Photonics Online*, May 12, 2000.

Article

Return to News & Community Home

CLEO 2000: Coiled fiber amplifiers produce high power single-mode pulses

5/12/2000 ***Bending multimode fiber amplifiers filters out higher-order modes without significantly reducing efficiency.***

By: Yvonne Carts-Powell

San Francisco, CA—The high intensity in fiber cores allows fiber lasers to produce nonlinear effects at relatively low powers, which is a boon for those who want to exploit these effects, but the bane of users who merely want high-power pulses from the relatively compact fiber lasers. Researchers at the Naval Research Laboratory (Washington, DC) and Sandia National Laboratories (Livermore, CA) have developed a simple method that allows more powerful single-transverse-mode pulses from multimode fiber amplifiers. The work is attractive because it uses a relatively common fiber design and it is both inexpensive and straightforward to implement: bend the amplifier.1

How it works

The work is based on an interesting property of fiber—all the modes propagating in fiber see bending loss, but the fundamental mode is the least sensitive to it. Jeffrey Koplow, and Lew Goldberg at NRL and Dahv Kliner at Sandia calculated 1.58 cm as an optical radius of curvature at which the lowest order mode (LP01) has minimal bending loss but all the higher order modes are high loss. Wrapping the gain fiber around a cylinder of this radius thus provides a form of distributed mode filtering.

One side-benefit of this method is that it can be used alone or combined with another method for increasing the output power of fiber amplifiers: using fibers with larger-than-normal cores and lower-than-normal numerical apertures (NAs). Just like with single-mode fibers, reducing the NA and increasing the dopant concentration in the multimode amplifier increases the stored energy and ability of the fiber to handle high peak power pulses.

"Exploiting bend loss to discriminate against higher-order modes allows the core diameter to be increased significantly beyond the single-mode limit," say the researchers, "allowing fiber lasers and amplifiers to be scaled up to much higher peak and average powers."

Kliner explains that by also using double-clad fiber, the pump absorption coefficient increases quadratically with core diameter. This allows users to either decrease the length of fiber or use larger higher-power pump sources without requiring much longer fibers.

Experimental system

The researchers constructed a coiled amplifier using double-clad fiber with a core diameter of 25 µm, a core NA of about 0.1, and a ytterbium concentration of about 1.5% by weight. The 200-µm-dia. hexagonal inner cladding layer (through which the pump light propagates) had a numerical aperture of 0.47, and the absorption coefficient at 975 nm was about 7.5 dB/m. The device was pumped by imaging the output of a fiber-coupled 974-nm diode array (with a 250-mm diameter and NA of 0.22) onto the polished end face of the fiber. The launched pump power was measured to be about 7.3 W.

According to the group, with the amplifier operated as an amplified spontaneous emission source, the M^2 of the output beam reached 1.09 ± 0.09, which is fairly close to diffraction-limited operation (an M^2 value of 1). When the coiled amplifier was seeded with 1064-nm light from a single longitudinal mode neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, the slope efficiency was similar to that of an uncoiled amplifier.

The technique allows researchers to scale pulsed fiber lasers and amplifiers to significantly higher pulse energies and peak powers, without trading higher power for lower beam quality. It could also be applied to raising the average power of CW fiber sources.

Reference

1. Jeffrey Koplow, Dahv Kliner, and Lew Goldberg, "Use of bend loss to obtain single-transverse-mode operation of a multimode fiber," Conference on Lasers and Electro-Optics (CLEO 2000), paper # CWJ6,

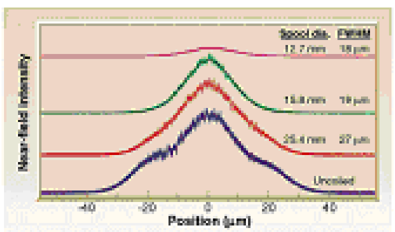
"**FIBER AMPLIFIERS: Coiling boosts single-mode power in multimode fiber**," Hassaun Jones-Bey, *Laser Focus World*, August 2000.

Laser Focus World

FIBER AMPLIFIERS: Coiling boosts single-mode power in multimode fiber

Researchers from Sandia National Laboratories (Livermore, CA) and the Naval Research Laboratory (NRL; Washington, DC) presented a technique for exceeding the current V-number limit of 2.405 for constructing a single-mode optical amplifier. The researchers expect the technique to allow scaling of pulsed fiber lasers and amplifiers to much higher powers than are currently attainable due to pulse-energy limitations caused by low energy storage and nonlinear processes in fiber.

The potentially ameliorative technique consists of coiling a multimode fiber and adjusting the radius of curvature to introduce a bend loss that preferentially suppresses signal modes of order higher than the fundamental. "If you strategically choose the radius of curvature, you can discriminate between the higher-order modes and the fundamental mode," said Dahv Kliner, a senior research scientist at Sandia who collaborated with Jeffrey Koplow and Lew Goldberg at the NRL to develop the technique. "So you can introduce a significant amount of loss for LP11, which is the first mode above the fundamental mode, and get a substantial suppression of LP11 and all higher-order modes compared to the fundamental mode LP01."



Asymmetric lobes indicate multi-mode operation in uncoiled curve at bottom. Ascending curves progressively take on smooth Gaussian symmetry with decreasing coil diameter until suppression of fundamental mode becomes evident in upper curve.

Click here to enlarge image

In their experiments, described during a technical presentation at the annual Conference on Lasers and Electro-Optics (CLEO; San Francisco, CA) in May, the researchers used a 6-m length of ytterbium-doped double-clad fiber with a core diameter of 25 µm and numerical aperture of 0.1, which yielded a V-number of 7.4 for a 1064-nm signal. A pump of 974 nm was used in the testing. Pump power was set at 3.9 W, and the near-field spatial profile of the copropagating amplified spontaneous emission (ASE) was measured by a linear diode array. ASE uniformly excites all modes of the fiber. A coil diameter of 1.58 cm enabled single-mode operation without excessive suppression of the fundamental mode (see figure).[1]

In comparing the slope efficiency of coiled and uncoiled versions of the amplifier seeded at 1064 nm, the researchers found a 2% difference, Kliner said. "In other words, we had not significantly compromised the performance of the amplifier. We had not induced significant bend loss to the lowest-order mode, so the slope efficiency was not changed." The amplifier threshold did change by about half a watt, he said, probably due to the filtering effect of removing the higher-order modes. They also measured a value for M^2 of 1.09 ±0.09 for the ASE source, essentially indistinguishable from unity within the accuracy of the measurement.

"**Coiled fiber amplifier delivers high-power signal**," Hassaun A. Jones-Bey, *Laser Focus World*, June 2002.

Laser Focus World

Coiled fiber amplifier delivers high-power signal

by Hassaun A. Jones-Bey

Single-mode, rare-earth-doped fiber lasers and amplifiers are widely used in optical telecommunications and other applications requiring compact, rugged, efficient light sources with diffraction-limited beam quality. Use of these sources for pulsed applications has been hindered, however, by the low pulse energies available compared to bulk solid-state lasers.

"People have gone a long way toward scaling up the continuous-wave power of fiber sources but those sources are still limited for pulsed applications, in terms of how much peak power you can get out," according to Dahv Kliner at Sandia National Laboratories (Livermore, CA). "And a lot of applications such as nonlinear frequency conversion, materials processing and lidar (light detection and ranging) require high-energy pulses."

Normally, pulse energy in fiber is limited by low energy storage as a result of amplified spontaneous emission and by the onset of nonlinear processes in the fiber. The simplest method to overcome both limitations is to increase the core size of the fiber, but this approach is restricted by the need to maintain single-transverse-mode operation. In practice, the upper limit for the core diameter of a single-mode fiber is about 10 μm for wavelengths near 1 μm.

Other methods for getting a multimode fiber to run single mode include controlling launch conditions or laser cavity configuration to preferentially excite the lowest-order mode; as well as controlling the dopant profile to preferentially amplify the lowest-order mode. "These methods aren't all necessarily competitive," Kliner said. "You can do several things at once. You can control the launch conditions as well as control the refractive-index profile to obtain even greater suppression of high-order modes."

Bend-loss approach

Several research groups are focusing on a range of approaches to the problem. Kliner, along with colleagues at the Naval Research Laboratory (Washington, DC), is investigating bend loss as a form of distributed spatial filtering. By strategically choosing the radius of curvature to discriminate against the higher-order modes, attainable pulse energy can be increased by

"**APPLIED PHYSICS: Powering Up in Single Mode**," Editor's Choice section in *Science 296*, 17b, April 5, 2002

CONTINUED FROM 15 EDITORS' CHOICE

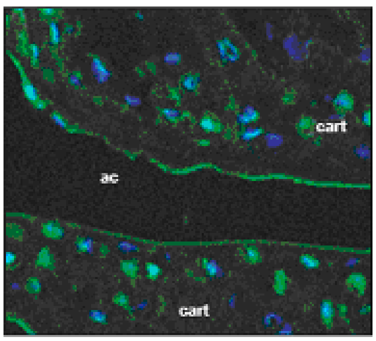
positive effects of estrogen on spatial learning and that its absence may increase the negative consequences of estrogen by removing a suppressive effect on ER-α–mediated activities. — LDC

Proc. Natl. Acad. Sci. U.S.A. **99**, 3996 (2002).

BIOMEDICINE

All Over the Joint

Rheumatoid arthritis is a debilitating and costly disease that affects over 2 million people in the United States; it is characterized by chronic inflammation of the synovial lining of the joints, which can ultimately lead to destruction of the joint and surrounding tissue. This inflammation is thought to be an autoimmune reaction, and the glycolytic enzyme glucose-6-phosphate isomerase (GPI) has been fingered as a likely target antigen. However, GPI is expressed in all tissues, so it has been difficult to explain why the immune attack is directed specifically to the joints.



GPI (green) on the cartilage surface (cart) lining the articular cavity (ac).

New insight into this puzzle emerges from Matsumoto *et al.*, who show that in healthy mice, GPI from the bloodstream selectively accumulates on the cartilage surface lining the joints. These joint-specific deposits of GPI were greatly amplified in a mouse model of rheumatoid arthritis. In complementary work, also with mice, Wipke *et al.* found that systemically injected antibodies against GPI localize within minutes to the peripheral joints and that this localization persists for at least 24 hours. These results support a model in which GPI (or other target antigens) exposed on the cartilage surface serves as a target for pathogenic autoantibodies, which in turn trigger an inflammatory cascade that proceeds unimpeded because cartilage lacks the normal cellular inhibitors of antibody-triggered immune attacks. — PAK

Nature Immunol. **3**, 360; 366 (2002).

APPLIED PHYSICS

Powering Up in Single Mode

Rare earth–doped optical fibers are compact and rugged light sources used in the telecommunication industry as lasers and optical amplifiers. For higher powered pulsed applications, their utility is somewhat hampered by the limited power they can carry and emit. One obvious alternative, increasing the diameter of the fiber, has the disadvantage of allowing light to propagate via many transverse modes. Di Teodoro *et al.* provide a simple solution by introducing a bend in the fiber of just the right geometry that suppresses propagation of the higher order modes. An ytterbium-doped multimode fiber 17 micrometers in diameter can operate in single mode when coiled around a 1.67-micrometer diameter spool and can achieve peak power in excess of 300 kilowatts. — ISO

Opt. Lett. **27**, 518 (2002).

HIGHLIGHTED IN *SCIENCE*'S SIGNAL TRANSDUCTION KNOWLEDGE ENVIRONMENT

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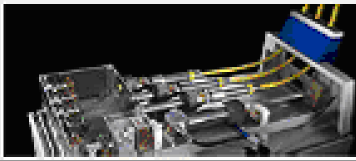
Fatty Acids and Synaptic Strength

Changes at synapses in the brain are thought to provide the cellular basis for learning and memory. The AMPA-type (α-amino-3-hydroxy-5-methylisoxazole-4-propionic acid) receptors for the excitatory transmitter glutamate are anchored in place at synapses through interactions with a scaffolding protein known as postsynaptic density protein–95 (PSD-95), which is known to be posttranslationally modified by addition of the fatty acid palmitate. El-Husseini *et al.* report that synaptic activity (corresponding to release of glutamate by the presynaptic neuron) enhances palmitate cycling on PSD-95 in cultured hippocampal neurons. Pharmacological inhibition of palmitoylation breaks up PSD-95 clusters and reduced AMPA receptor–mediated signaling. Thus, activity-dependent depalmitoylation of PSD-95 provides a new mechanism for the regulation of synaptic function. — LBR

Cell **108**, 849 (2002).

"**LASER MARKETPLACE 2007: Laser industry navigates its way back to profitability**," *Laser Focus World,* January 2007.



Laser Focus World

LASER MARKETPLACE 2007: Laser industry navigates its way back to profitability

It's been a few years in the making, but 2006 yielded some very positive returns.

KATHY KINCADE AND STEPHEN G. ANDERSON

There's nothing quite like taking a calculated risk-marrying instinct with intellect-and watching it pay off. Whether in business, investment, R&D, sports, or life, we surround ourselves with the right tools, data, and people to ensure an optimal return. Even so, at the end of the day, it's all still a bit of a gamble. For the last five years this industry has worked hard to strike the right balance between the "sure thing" and the "next big thing"-and this focused effort appears to be yielding some positive returns. After a lackluster 2005, the worldwide laser business experienced a surprisingly strong 2006-thanks in large part to better-than-expected performance by the semiconductor industry and to the continuing rebound of optical communications, among other factors. Looking forward, the industry's mood seems to be one of optimism tempered by concern centered around the level of investment in the semiconductor arena for 2007 and general wariness related to economic conditions.

At first glance the results of our survey might appear to contradict this scenario. Global revenue growth for all lasers for 2006 over 2005 was just 2%. However, a look at the underlying detail reveals that nondiode laser sales actually gained 11% for this period and that positive unit growth for diode lasers into 2006 was in fact offset by average price declines-producing a revenue change of -4%. For 2007, we expect a global revenue increase of 8% for all lasers with total sales exceeding $6 billion for the first time (see Fig. 1). We should note too that (because we report revenue in current U.S. dollars) price changes can result from exchange-rate fluctuations that occur during the year . . . and in fact some of the diode-laser revenue decline results from the decline in the value of the yen against the dollar. At the same time, though, the U.S. dollar is currently at a 20-month low against the euro, creating the opposite effect for lasers manufactured in Euro-zone countries.

"**Fiber Laser Technology Review**," a webcast presentation by Andrew Held of Nufern, May 17, 2006.

Fiber Lasers - Technology & Applications

Originally Broadcast: May 17, 2006
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Length: 1 hour, including Q&A
Speakers: Andy Held, VP Sales/Marketing, Nufern

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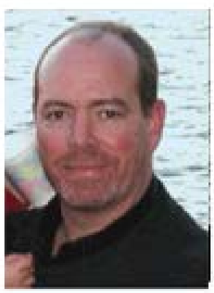
Overview:
FIBER LASERS are being commercially adopted at a rate faster than any previous laser technology, with "real world" applications ranging from marking to remote sensing. In this Webcast Andy Held, VP Sales and Marketing at Nufern (East Granby, CT) will review the technology underpinning of fiber lasers and the characteristics that make them such an attractive value proposition. He will then focus on current applications trends -- from the growing acceptance of high-power fiber lasers for industrial applications, to the many emerging opportunities in applications like medicine and the graphic arts. Technical challenges as well as market issues will be covered.

About the Presenters:
(Click presenter's name for more information)

Andy Held
VP Sales/Marketing
Nufern



Fiber Laser Technology Review

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